



**Reduction of Shear and Flatwise
Tension Strength in F-111
Honeycomb Panels Exposed to
Moisture**

Richard A. Bartholomeusz

DSTO-TR-1331

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Richard A. Bartholomeusz

**Air Vehicles Division
Aeronautical and Maritime Research Laboratory**

DSTO-TR-1331

ABSTRACT

Many of the fuselage panels and control surfaces on the Royal Australian Air Force (RAAF) F-111 aircraft are made up of bonded sandwich panels. These panels are made up of thin facings of metallic sheet that are bonded to aluminium honeycomb core. A survey of RAAF aircraft showed that these panels are susceptible to damage and deterioration through exposure to moisture. A test program was conducted to quantify the effect moisture has on the shear and flatwise tension strength of this type of panel. Coupons specimens representative of the Australian fleet were manufactured and exposed to moisture. These specimens were tested over a 6 month period and it was found that moisture dramatically reduces the strength of exposed panels.

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Executive Summary

Many of the fixed and removable panels on the Royal Australian Air Force F-111 aircraft are made up of thin metallic face sheets, bonded to aluminium honeycomb core. These panels make up the majority of the fuselage skins and control surfaces of the aircraft. These panels have an excellent stiffness to weight ratio and are thus particularly useful in aerospace applications. In sandwich structures, the core sustains the shear load, while the faces take compressive and tensile bending loads, and resists the shear and normal loads in the plane of the structure.

A serious problem for these panels is the degradation of the adhesive bond that connects the face sheets to the core. Work has shown that these bonds are particularly susceptible to degradation through exposure to moisture. This type of degradation is gradual and difficult to detect through conventional NDI techniques. This has led to a number of in-flight failures, failure of panels during repair and an increased maintenance burden in assessing and repairing damage. Therefore, it was important to gain an understanding of the effect that degradation would have on panel strength in order to increase the safety of flight and reduce maintenance costs.

To quantify the effect of bond degradation on the strength of sandwich panels a laboratory based test program was undertaken. This entailed manufacture of coupon specimens representative of the materials and construction of typical F-111 panels. These coupons were exposed to moisture over a 6-month period. Samples were withdrawn at stages and tested in flat wise tension and shear (shear is the dominant load case in such panels). A 63% reduction in shear strength and 50% reduction in flat wise tension strength and were noted over the period of the trial. Some recovery of strength occurred when panels were dried after exposure for 6 months.

These results indicate that degradation of the bond may be a serious issue for the structural integrity of F-111 panels if moisture was able to penetrate into the interior. This implies that sealing of the panels to prevent moisture ingress is vital. Also, it suggests that during routine inspections of such panels particular attention should be paid to areas that are susceptible to moisture ingress such as edge members, fastener holes, old repairs and foreign object damage.

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Richard Bartholomeusz graduated from the Royal Melbourne Institute of Technology with a Bachelor of Aeronautical Engineering. On completion of his degree he joined the Royal Australian Navy as an Aircraft Engineering Officer working on an operational helicopter squadron. He has completed an Associate Diploma in Management and a Graduate Diploma in Aircraft Engineering Management. After joining DSTO, Richard has been involved in the design, development and testing of advanced composites and adhesively bonded joints. In particular, he has worked on the development of battle damage repair techniques and the manufacture and design of composite structures. His areas of interest are the use of composite materials and bonded joints in aircraft structural repair.

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1. Introduction

Many of the fixed and removable panels on the Royal Australian Air Force F-111 aircraft are made up of thin metallic face sheets, bonded to aluminium honeycomb core. These panels make up the majority of the fuselage skins and control surfaces of the aircraft (Figure 1). Such panels have an excellent stiffness to weight ratio and are thus particularly useful in aerospace applications explaining their wide use in the F-111. In sandwich structures, the core sustains the shear load, while the faces take compressive and tensile bending loads, and resists the shear and normal loads in the plane of the structure.

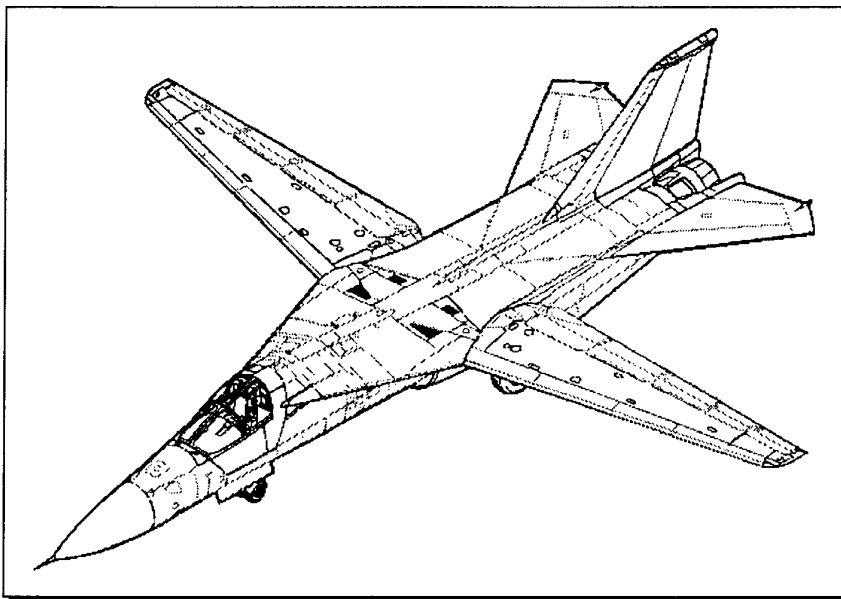


Figure 1: F-111 aircraft showing bonded sandwich panels.

The dominant load case for the F-111 bonded panels is shear caused by in-plane torsion, fuselage shear, bending and out-of-plane normal pressure loads. Normal pressure loads also lead to tensile forces acting normal to the panel face leading to flat-wise tension in the face to core bond. Bending loads also can lead to local buckling or crippling of the faces which may cause peeling of the face to core bond [1].

A serious problem for these panels is the degradation of the adhesive bond that connects the face sheets to the core and the core nodes [2]. Work has shown that these bonds are particularly susceptible to degradation through exposure to moisture [3]. This type of degradation is gradual and difficult to detect through conventional NDI techniques. As a consequence a number of in-flight failures, failure of panels during repair and an increased maintenance burden in assessing and repairing damage has

occurred. Therefore, it was important to gain an understanding of effect degradation would have on panel strength to increase safety of flight and reduce maintenance costs.

To quantify the effect of bond degradation on the strength of sandwich panels a laboratory-based test program was undertaken. This entailed manufacture of coupon specimens representative of the materials and construction of typical F-111 panels. A baseline condition of as manufactured was tested in flat-wise tension and shear. The remaining coupons were exposed to moisture over a 20 to 26-week period. Samples were withdrawn at stages and tested in shear and flat-wise tension at room temperature. An average reduction of 63% in shear strength and 50% reduction in flat-wise tension strength was noted over the period of the trial. Some recovery of strength was noted when panels were subsequently dried after initial exposure to moisture and tested. Similar laboratory trials conducted at DSTO also show that the peel strength of bonded panels degrades with exposure to high humidity [4].

2. Representative Specimens

To understand the effect of moisture on the F-111 panels it was important to represent as closely as possible the conditions and construction of the aircraft. Issues such as loading, material types, manufacturing procedures and environmental conditions were considered in the design of a representative test program. The differences in material type and manufacturing processes apparent for panels that were either part of the original build, the rebuild program or current repair procedures were considered. These are discussed in more detail below.

2.1 Load Cases

A review of bonded panel design coupled with some simple analysis showed that the dominant load for F-111 bonded panels was shear [1]. It was also deduced that peel and flat-wise tension loading would play a part in the failure of such panels. A coupon specimen that would replicate the materials used in the manufacture of bonded panels and represent the major load cases was required. A review of available specimens and test methods showed that ASTM C 393-94 [5] could be used to examine the shear strength and modulus of bonded panels (Figure 2). Similarly, the flat-wise tension strength could be determined using the portable adhesion test method based on ASTM D 4541-95 [6] (Figure 2). The test program for the peel load case is reported elsewhere as mentioned earlier [4].

2.2 Materials

A survey of materials used on the F-111 showed that at least four adhesive and two honeycomb core types were used in the original build, rebuild and repair of bonded sandwich panels. These materials are detailed in Table 1 and show the adhesive and

core combinations used in panel construction. The face sheets or skins of most of the panels were manufactured from 2024-T81 Aluminium Alloy.

An additional consideration for the honeycomb core material is the ribbon direction. Honeycomb core is manufactured from ribbons of aluminium alloy that are bonded at evenly spaced nodes and then expanded to form a hexagon shaped cellular material. Quoted values for honeycomb core indicate that the shear strength is higher in the ribbon direction than in the node bond direction. This is because the node bond adhesive shear strength is lower than that of the shear strength of the contiguous aluminium ribbon. To make the test program conservative the majority of specimens were made with the ribbon direction across the width ensuring that the core node bond would be stressed during testing. This also assumes that the node bond adhesive is more likely to degrade than the aluminium ribbon and thus affect the panel shear strength. Failure of core node bonds has been observed in practice supporting this assumption. One set of specimens was made with the ribbon direction parallel to the length of the specimen using AF131-2 adhesive to test this hypothesis.

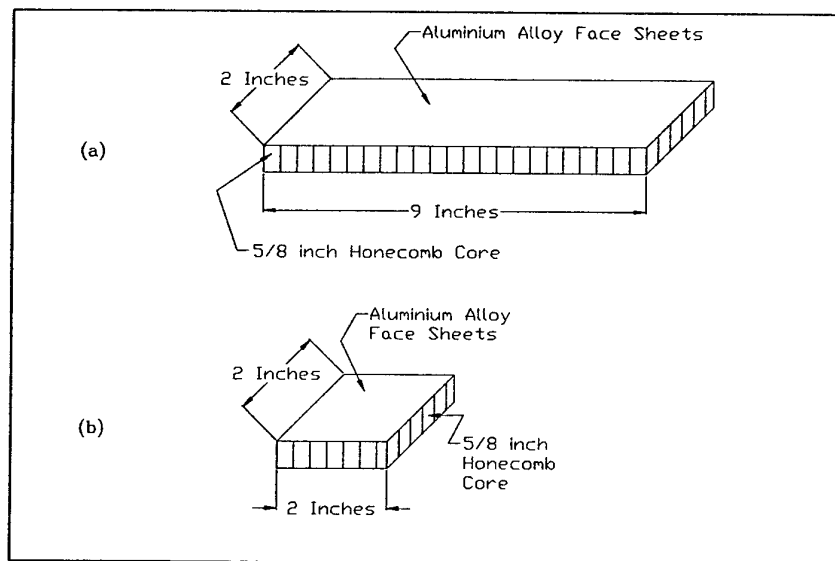


Figure 2(a) and (b): Shear and flat-wise tension representative specimens.

Table 1: Materials used for sandwich panel construction [4].

| Material | Details | Used in |
|--------------------------------------|---|---|
| Alcore 5056 Untreated Honeycomb Core | Cell size 3/16", thickness 5/8", foil gauge 0.002", polyamide node adhesive, 5056 Aluminium Alloy. | Original Manufacture |
| Alcore Dura-Core Honeycomb Core | Cell size 3/16", thickness 5/8", foil gauge 0.002", polyamide node adhesive, 5056 Aluminium Alloy. Foil has a protective chromium based coating. | Rebuild and Current Repairs |
| JD Lincoln L-313 Adhesive | High peel strength, flame retardant, modified epoxy, cured at 177°C, 25-50 psi for 60 minutes. | Rebuild programs |
| AF130-2 Adhesive | Modified epoxy film adhesive, cured at 177°C and 50psi for 60 minutes. | Original Manufacture |
| AF131-2 Adhesive | High temperature modified epoxy film adhesive with Kevlar filler, cured at 177°C and 50psi for 60 minutes. | Original Manufacture |
| FM300 Adhesive | Modified epoxy film adhesive, cured at 177°C and 50psi for 60 minutes. | Current Repairs |
| 2024-T81 Aluminium Alloy | All face sheets or skins manufactured from 0.0020 inch thick Aluminium Alloy. | Original Manufacture, Rebuild and Current Repairs |

2.3 Manufacturing Procedures

2.3.1 Pre-Bonding Surface Treatment

Degradation in adhesive bonds is largely dependant on the type of surface treatment applied to metallic adherends prior to bonding. As such, the different treatments used in the original manufacture, rebuild and repair of such panels were covered in the representative coupon testing.

During the original build and the rebuild program of the F-111 panels the metallic face sheets were pre treated with a chromic acid etch (CAE) prior to bonding. Current repair techniques call for the use of the DSTO developed Silane pre-bonding treatment to be used on metallic panels [7]. In all cases the honeycomb core was degreased with Methyl Ethyl Ketone (MEK) to remove contaminants prior to bonding.

2.3.2 Panel Bonding

During the original build and rebuild programs the face sheets, core and adhesive were assembled in a tool after all bonding surfaces were treated. The adhesive was then cured in an autoclave under positive pressure and elevated temperatures to bond the panels. Current repair techniques call for adhesive curing to be conducted under vacuum bags using controlled local heating. For the current test program it was decided that adhesive pressurisation and heating would have a secondary effect on the degradation mechanisms in such panels. As such the current repair techniques were not evaluated and all panels were bonded in an autoclave under positive pressure using the recommended cure cycle for the adhesives as in original build and rebuild.

2.4 Environment

Earlier work determined that two mechanisms were active in the degradation of F-111 panels [1]. The first was direct exposure of the bond and core to moisture leaking into panels through damage, poor sealing or poor repairs (designated "Direct Ingress" specimens). The second mechanism was believed to be caused by moisture transporting through the honeycomb core bonds (designated "Moisture Transport" specimens). As such, two specimen types; one that allowed direct ingress of moisture through holes in one of the face sheets and through the unsealed panel edges (see Figure 3) and one that only allowed moisture in through unsealed panel edges (Moisture Transport) were designed (see Figure 4). For the Direct Ingress specimens the 1 mm holes were drilled at a spacing of 12.5 mm.

Exposure to a real ambient environment such as the tropical conditions the aircraft experiences at RAAF Amberley would cause slow degradation in the panels. Due to time constraints, an accelerated laboratory test program was required. As such, the Direct Ingress specimens were exposed to an environment of 70°C with condensing humidity and the Moisture Transport specimens were immersed in water at 70°C. Earlier studies showed that these environmental conditions were suitable for the accelerated degradation of honeycomb panels [8].

2.5 Summary

A summary detailing the materials, manufacturing process and designation for the four types of representative specimens is given in Table 2. Both shear and flat-wise tension loading specimens were manufactured for each of the four types.

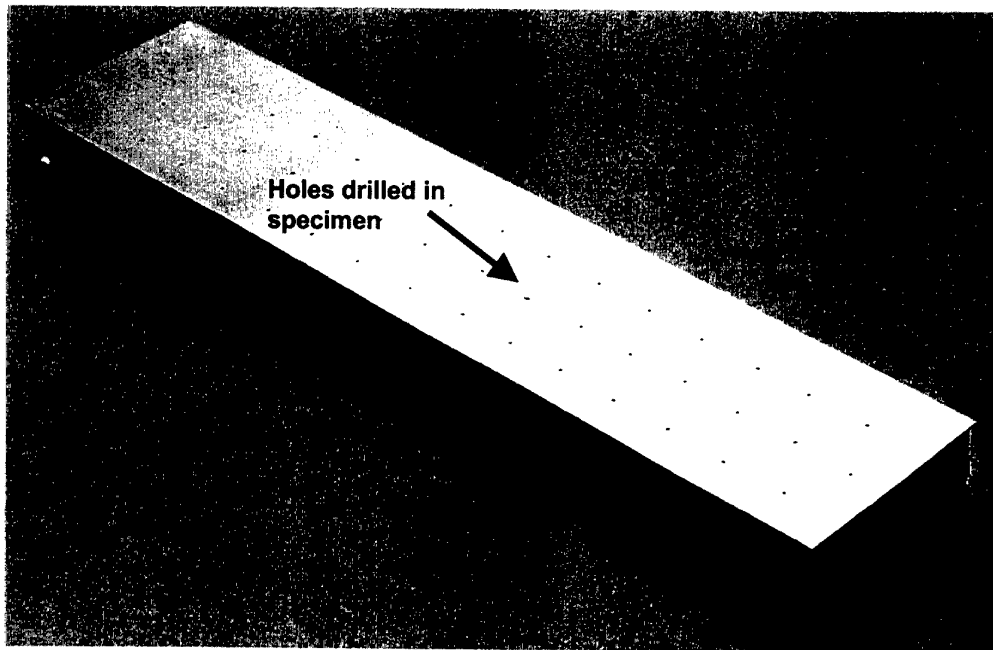


Figure 3: Moisture Direct Ingress Specimen.

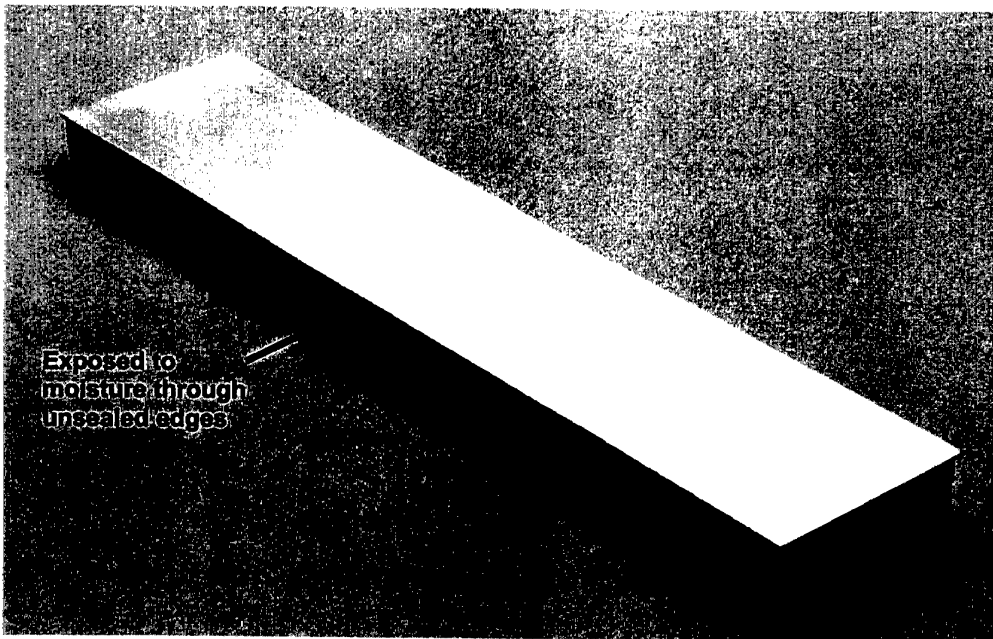


Figure 4: Moisture Transport Specimen.

Table 2: Summary of specimen types in test program.

| <i>Specimen Designation</i> | <i>Materials</i> | <i>Bonding Processes</i> | <i>Environment</i> |
|-----------------------------|--|---|---|
| Original Build AF130-2 | 2024-T81 Aluminium Alloy, Face Sheets, Alcore 5056 Untreated Honeycomb and AF130-2 Adhesive | Chromic Acid Etch face sheets, degrease core, bond under positive pressure at elevated temperature. | 70°C plus condensing humidity with direct access through holes in face sheets or immersed in water with unsealed honeycomb core edges. |
| Original Build AF131-2 | 2024-T81 Aluminium Alloy, Face Sheets, Alcore 5056 Untreated Honeycomb and AF131-2 Adhesive | Chromic Acid Etch face sheets, degrease core, bond under positive pressure at elevated temperature. | 70°C plus condensing humidity with direct access through holes in face sheets or immersed in water with unsealed honeycomb core edges.. |
| Rebuild | 2024-T81 Aluminium Alloy, Face Sheets, Alcore Dura-Core Honeycomb and JD Lincoln L-313 adhesive. | Chromic Acid Etch face sheets, degrease core, bond under positive pressure at elevated temperature. | 70°C plus condensing humidity with direct access through holes in face sheets or immersed in water with unsealed honeycomb core edges. |
| Current Repair | 2024-T81 Aluminium Alloy, Face Sheets, Alcore Dura-Core Honeycomb and FM300 adhesive. | Silane treat face sheets, degrease core, bond under positive pressure at elevated temperature. | 70°C plus condensing humidity with direct access through holes in face sheets or immersed in water with unsealed honeycomb core edges. |

3. Test Regime

Initially a set of as-manufactured or baseline shear and flat-wise tension tests were carried out. For the shear tests the specimens were loaded in four point bending. For the flat-wise tension tests the portable adhesion test method was used. After baseline testing the remaining direct moisture ingress specimens were immersed in water in an attempt to fill some of the cells prior to placing them in a humidity chamber at 70°C with condensing humidity. All of the untested moisture transport specimens were immersed in water at 70°C.

Flatwise tension specimens were withdrawn every two weeks and tested. The reduction of strength was monitored. The Current Repair shear specimens were also tested regularly to monitor the drop in shear strength over time with exposure.

Unfortunately, only a small amount of some of the original manufacture and rebuild materials were available and thus fewer of these types of shear specimen were made. To understand the full effect of degradation on the shear strength it was important to conduct tests after the specimens were degraded by exposure to moisture. The results of the flat-wise tension tests were used as a guide to indicate when the shear specimens

were degraded. Thus the Original Build and Rebuild shear specimens were tested after signs of degradation were evident in the flat-wise tension results.

A small number of Current Repair Shear and Original Build AF131-2 and Current Repair Flat-wise Tension specimens were dried after moisture exposure to determine whether any recovery of strength was possible after degradation. These specimens were dried at 80°C in an oven for 10 weeks and then either tested in four-point bend or using the portable adhesion tester.

4. Results

Figure 5 and Figure 6 show the change in shear and flat-wise tension strength respectively for the bonded panels exposed to direct moisture in a 70°C condensing humidity environment. Figure 7 shows the change in shear strength for the bonded panels exposed to moisture from the panel edges. This Figure also shows change in shear strength for a panel with the ribbon direction parallel to the length dimension of the panel. These specimens were designated as "Original Build AF131-2 RD" and were also exposed to moisture only through the panel edges. Figure 8 shows the change in flat-wise tension strength for the bonded panels exposed to moisture from the panel edges.

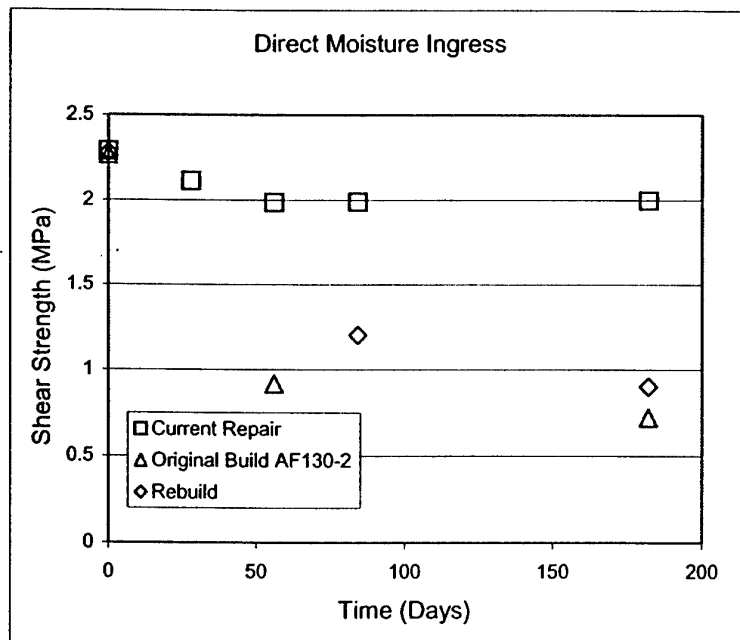


Figure 5: Honeycomb panel shear strength as a function of exposure to moisture by direct ingress in an environment of 70°C condensing humidity.

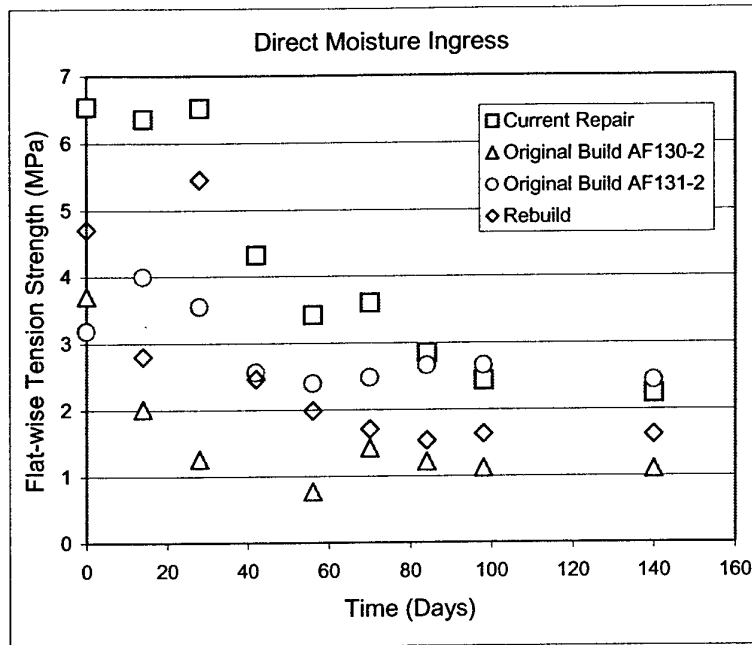


Figure 6: Honeycomb panel flat-wise tension strength as a function of exposure to moisture by direct ingress in an environment of 70°C condensing humidity.

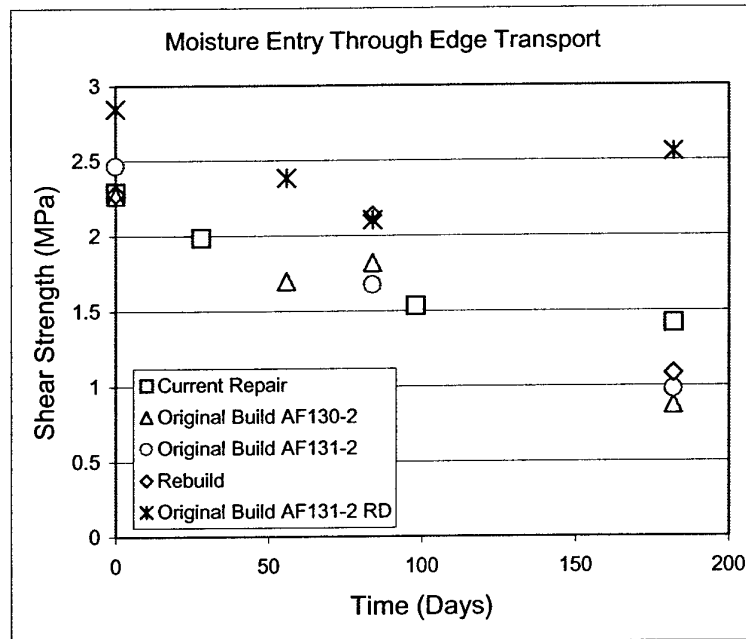


Figure 7: Honeycomb panel shear strength as a function of exposure to moisture from the honeycomb core edges. Panels were immersed in water at 70°C. Results designated "Original Build AF131-2 RD" was for specimens with the ribbon direction parallel to the length dimension.

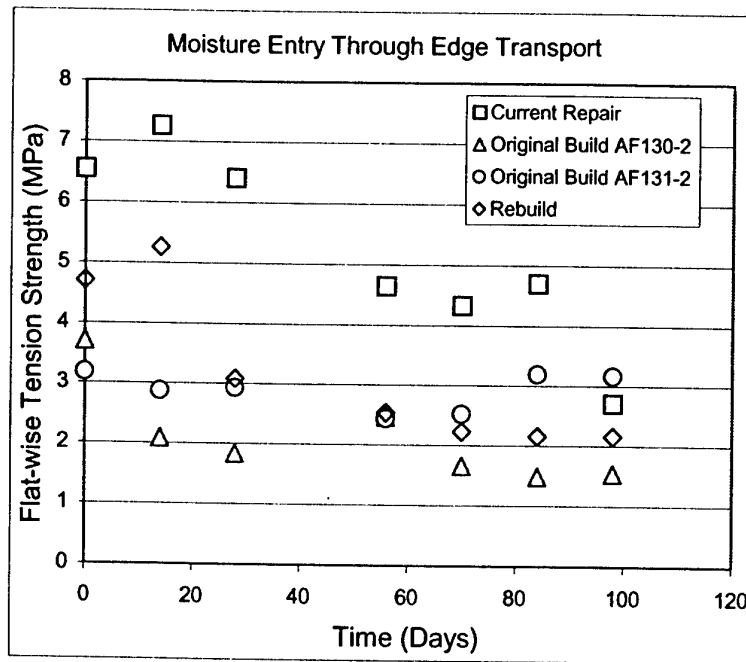


Figure 8: Honeycomb panel flat-wise tension strength as a function of exposure to moisture from the edges. Panels were immersed in water at 70°C.

The results of the shear and flat-wise tension tests carried out on the Original Build AF131-2 and Current Repair specimens after drying are summarised in Table 3.

Table 3: Results of shear and flat-wise tension tests on Original Build AF131-2 and Current Repair specimens after drying at 80°C for 10 weeks.

| Specimen Designation | Average Baseline Strength (MPa) | Average Degraded Strength (MPa) | Average Strength Recovery After Drying (MPa) |
|--|---------------------------------|---------------------------------|--|
| Original Build AF131-2 (Flat-wise Tension) | 3.18 | 2.45 | 3.08 |
| Current Repair (Flat-wise Tension) | 6.54 | 1.71 | 2.22 |
| Current Repair (Shear) | 2.29 | 2.24 | 5.12 |

A summary of results showing the effect degradation has on the shear and flat-wise tension strength for the different specimens is shown in Figure 9. Also shown in the same Figure is the recovered shear and flat-wise tension strength for the Current Repair specimens and the recovered flat-wise tension strength for the Original Build AF131-2 specimens.

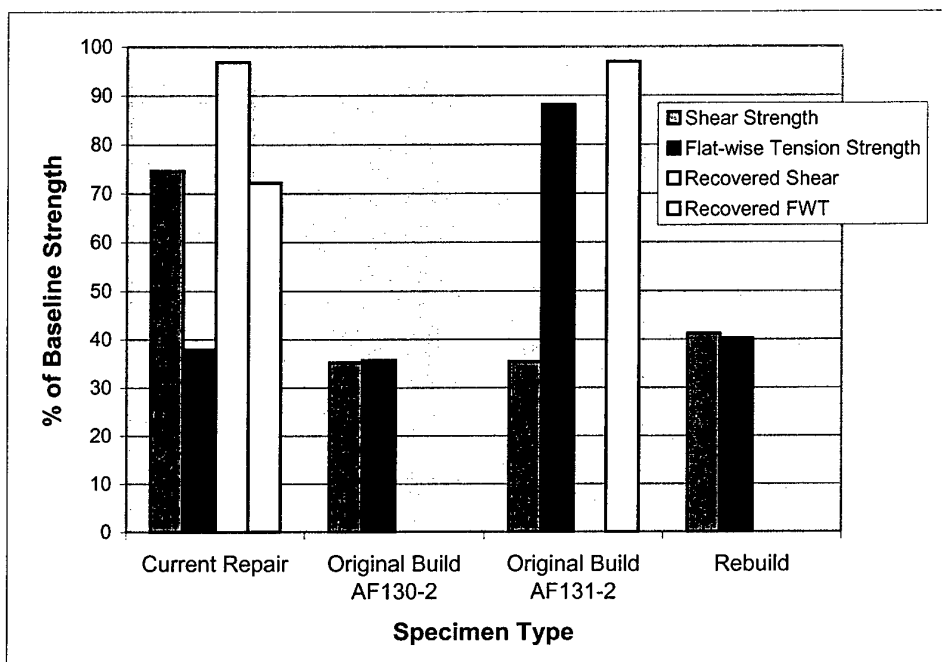


Figure 9: Percentage of baseline shear and flat-wise tension strength after degradation for all specimen types. Also shown are the shear and flat-wise tension strength recovery after drying for the Current Repair and Original Build AF131-2 specimens.

5. Discussion

The data in Figure 5 and Figure 7 show that for the Original Build and Rebuild specimens the shear strength reduces dramatically with exposure to moisture. On average the shear strength reduced 63% for these specimens (Figure 9). These specimens are representative of the existing honeycomb sandwich panels on the aircraft and as such degradation of the shear strength in these panels is a major concern after exposure to moisture. For the Current Repair specimens the shear strength reduced by 25%.

The Current Repair procedures call for the use of Dura-Core honeycomb where the nodes are pre-treated with a protective chromium based coating before bonding. Also, the repair patches are surface treated using the DSTO developed Silane pre-bonding surface treatment that produces high strength and durable bonds [9]. As such the shear strength of the Current Repair specimens were less affected by moisture. This implies that repairs applied to honeycomb panels on the F-111 aircraft with these methods and materials are more resistant to moisture degradation.

The difference in degradation levels between the specimens representative of the aircraft build condition and repair procedures can be attributed to the difference in the

materials and bonding processes used during the manufacture of the honeycomb core and the sandwich panels. The panels on the aircraft are manufactured using first generation pre bonding surface treatments that are easily degraded when exposed to moisture. In particular, the lack of surface treatment during manufacture of the honeycomb core node bonds allows these bonds to degrade rapidly and affect the shear strength. Also, work has shown that the layer of adhesive between the node faces has gaps and this allows water to rapidly move from cell to cell [8] contributing to the degradation mechanism.

Figure 7 shows that for the Original Build AF131-2 specimens with the ribbon direction parallel to the length the shear strength does not change with exposure. This was expected, as the shear strength of the honeycomb core aluminium foil is less likely to degrade than the core node bond.

The flat-wise tension strength reduces for all specimen types with exposure time (see Figure 6 and Figure 8). The average reduction was 50% and the best performed was the Original Build AF131-2 specimens with a 12% reduction in strength (Figure 9). All the degraded specimens fail at the core to skin bond through adhesive fillet/core pull out [8]. This implies that the bond between the adhesive and the core is the weak link. This is expected as in all cases the core is only degreased prior to bonding and it is known that this is a poor surface treatment method.

Table 3 and Figure 9 also show that after drying it is possible to recover some of the shear and flat-wise tension strength lost during exposure to moisture. Unfortunately, only a small sample of specimens was available at the end of the test program to examine the effect of drying on strength. More work would be required make any recommendations regarding strength recovery after drying.

6. Conclusions

1. Exposure to moisture considerably reduces the shear strength and flat-wise tension strength of the bonded honeycomb sandwich panels used in the manufacture and rebuild of the F-111. The shear strength reduces by 63% and the flat-wise tension strength reduces by 50%.
2. The untreated honeycomb used in the manufacture of the F-111 bonded panels is susceptible to failure in shear through core node bond degradation due to lack of adequate surface treatment prior to bonding.
3. The materials and processes (in particular the use of advanced pre-bonding surface treatments developed at DSTO) used in current repair practices are less susceptible to degradation.

4. The shear strength of bonded panels in the ribbon direction is less susceptible to degradation as the aluminium alloy ribbons used in honeycomb do not degrade rapidly.
5. The bond between the adhesive and the honeycomb core fails during flat-wise tension testing implying that the surface treatment of the core prior to bonding was inadequate.
6. Some of the shear and flat-wise tension strength of bonded panels may be recovered after degradation by drying the panels at 80°C for 10 weeks.
7. These results indicate that degradation of the bond may be a serious issue for the structural integrity of F-111 panels if moisture was able to penetrate into the interior. This implies that sealing of the panels to prevent damage and corrosion through moisture ingress is vital.
8. During routine inspections of such panels particular attention should be paid to areas that are susceptible to moisture ingress such as edge members, fastener holes, old repairs and foreign object damage.

7. Acknowledgements

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Richard A. Bartholomeusz

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| 19. ABSTRACT Many of the fuselage panels and control surfaces on the Royal Australian Air Force (RAAF) F-111 aircraft are made up of bonded sandwich panels. These panels are made up of thin facings of metallic sheet that are bonded to aluminium honeycomb core. A survey of RAAF aircraft showed that these panels are susceptible to damage and deterioration through exposure to moisture. A test program was conducted to quantify the effect moisture has on the shear and flatwise tension strength of this type of panel. Coupons specimens representative of the Australian fleet were manufactured and exposed to moisture. These specimens were tested over a 6 month period and it was found that moisture dramatically reduces the strength of exposed panels. | | | | | | | |